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Abstract

An electromagnetic NDE technique for measuring the crack opening displacement of surface fatigue cracks is described. A ferromagnetic resonance probe utilizing yttrium-iron-garnet was used to induce eddy currents in an aluminum plate. The crack opening displacement of a semi-elliptical fatigue crack evaluated at the surface was measured optically at several values of bending stress on the specimen. A technique is presented which allows the crack depth to be calculated from the measured COD at a given stress. The relative phase and magnitude of input vs. output signal to and from the resonating YIG sphere was recorded during the interaction of the FMR probe eddy currents and the fatigue crack. A method is shown to extract quantitative information from these signals and to correlate this information with the crack opening displacement.

Keywords

Nondestructive Evaluation

Disciplines

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MEASUREMENT OF SURFACE CRACK OPENING DISPLACEMENTS USING MICROWAVE FREQUENCY EDDY CURRENTS

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ABSTRACT

An electromagnetic NDE technique for measuring the crack opening displacement of surface fatigue cracks is described. A ferromagnetic resonance probe utilizing yttrium-iron-garnet was used to induce eddy currents in an aluminum plate. The crack opening displacement of a semi-elliptical fatigue crack evaluated at the surface was measured optically at several values of bending stress on the specimen. A technique is presented which allows the crack depth to be calculated from the measured COD at a given stress. The relative phase and magnitude of input vs. output signal to and from the resonating YIG sphere was recorded during the interaction of the FMR probe eddy currents and the fatigue crack. A method is shown to extract quantitative information from these signals and to correlate this information with the crack opening displacement.

INTRODUCTION

We describe here a new microwave frequency eddy current technique for nondestructive evaluation of the surface crack opening displacement of fatigue cracks. The flaw type treated in this paper consists of a flat, semi-elliptical shaped crack in a 2024 aluminum plate. The procedure is to induce eddy currents to flow in the vicinity of an open fatigue with a ferromagnetic resonance probe, and to measure the changes in the probe's reflection coefficient as the probe is translated across the crack. These measurements are performed at a frequency of approximately one Gigahertz so that the skin depth of the eddy currents will be small relative to the magnitude of the crack opening displacement.

The combined effects of the uniform precession and higher order magnetostatic modes excited in the yttrium-iron-garnet sphere induce eddy currents near the surface of the specimen. The presence of the open crack disrupts these patterns, and couples the crack electronically with the resonance in the YIG sphere. This coupling is seen to change as the sphere is translated across an open surface crack, in a direction along the normal to the crack plane. The change in coupling produces changes in the probe's reflection coefficient. As the probe scans an open crack, the changes in reflection coefficient are recorded on a Smith chart. During a scan, these changes produce a closed figure which is reproducible, and rich in geometric information. The quantified information obtained from this type of scan varies linearly with the optically measured surface crack opening displacement. Additionally, changes in the probe reflection coefficients are seen to give valuable information concerning the crack closure stress of surface fatigue cracks.

MEASUREMENT OF CRACK OPENING

We define the surface crack opening displacement as $\Delta u_z(0,0)$ where subscript z indicates the displacement across the crack faces in the z direction evaluated at $(x,y) = (0,0)$. See Fig. 1. Additionally, we adopt the notation for $a \equiv$ crack depth, and $c \equiv$ crack half-width. The crack resides in a $\frac{1}{2}$ in. thick by $2\frac{1}{2}$ in. wide bar of 2024 aluminum which is loaded in three point bending by an

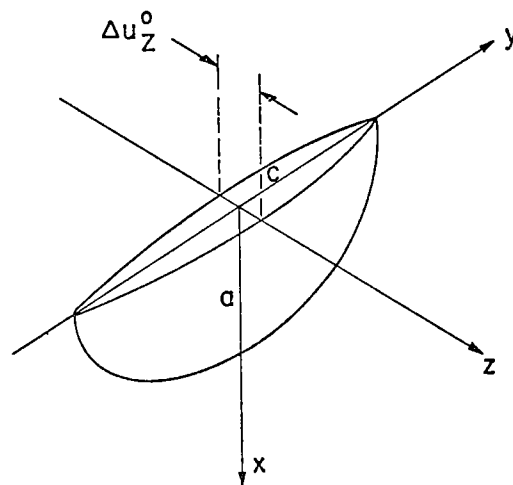


Fig. 1 Crack coordinate system.

MTS System 810 servohydraulic testing machine. In this paper, we will refer to stress σ as the maximum tensile stress evaluated at the surface of the beam at $(x,y,z) = (0,0,0)$.

A ferromagnetic resonance probe with a 30 mil YIG sphere is prepared to measure crack opening in the following manner. The probe is positioned above the aluminum surface with a lift-off, $h=25$ microns. See Fig. 2. An input signal with a center frequency of approximately one Gigahertz with a sweep range of 100 Megahertz is applied at the terminals of the loop of wire surrounding the YIG sphere. A samarium-cobalt magnet is placed near the sphere to apply a DC bias magnetic field. In Fig. 3, we see the Smith chart response of the probe in this configuration, where the radial distance from the diagram center indicates the magnitude of the reflection coefficient $|r|$, and θ is the phase angle between the incident and reflected signals. The large loop indicates the excitation of the uniform precession which behaves like a magnetic dipole. The smaller loop indicates the excitation of a higher order magnetostatic mode, which may alternatively be modeled as a multipole.

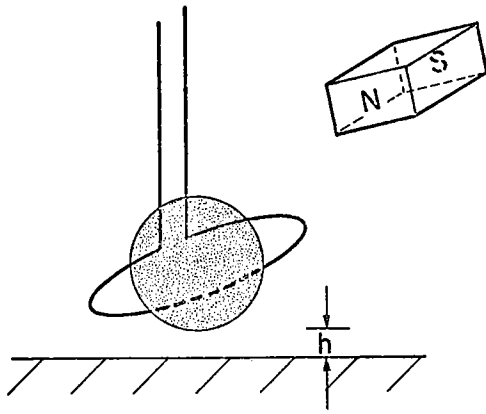


Fig. 2 Ferromagnetic resonance probe near surface.

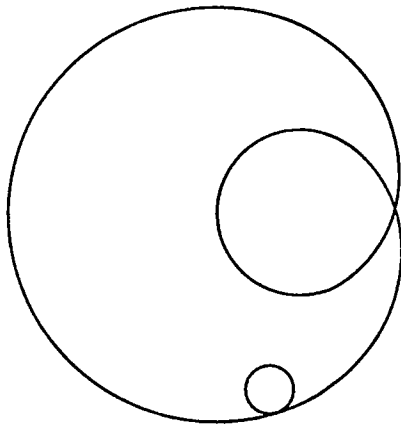


Fig. 3 Smith chart showing uniform precession with higher order resonance.

The electronic modeling of the coupling between these modes is presented in detail in a companion paper by Auld et al ². With the probe adjusted so that a higher order resonance is near the frequency of the uniform precession, we adjust the input frequency to the center frequency of the uniform precession. At this fixed frequency we place the probe over an open fatigue crack a distance h from the surface. See Fig. 4. In our tests we set the lift-off, h , to 25 microns. At this value of lift-off the probe is placed approximately 10 mils from the crack. The probe is then translated over the crack at 5 mils/sec until the probe is past the crack by 10 mils. During this translation, the fixed frequency reflection coefficient of the FMR probe is recorded on a x-y recorder. See Fig. 5. This figure shows the features of a crack signature obtained from a scan of an open fatigue crack. The lift off curve is obtained by translating the probe vertically above the crack from the surface to 75 microns above the surface. Then at a near constant value of 25 microns of lift-off, during lateral translation of the probe, the double loop pattern is traced out as the reflection coefficient varies. We have found that the presence of the primary loop corresponds to presence of the fatigue crack, regardless of whether the crack is open or not. The secondary loop has been found to correspond to the amount the crack faces are displaced due to the applied

stress. Since the total size of the primary and loops changes somewhat for variations in lift-off, we normalize the crack signature by computing a figure of merit which we call the loop ratio for each value of crack opening. This ratio is simply the amplitude of the secondary loop divided by the amplitude of the primary loop.

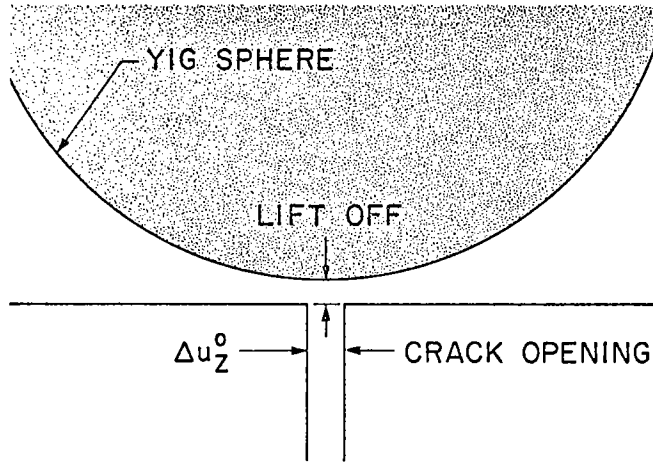


Fig. 4 YIG sphere of FMR probe above open fatigue crack.

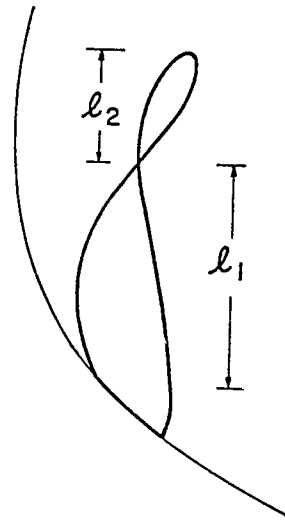


Fig. 5 Crack signature with primary and secondary loops identified.

In Fig. 6 we see the crack signature obtained from a fatigue crack at three different values of bending stress. At zero stress, the crack is completely closed, and we see only the primary loop. At 50 MPa the crack has opened only about 1 micron, and the secondary loop just begins to form. At 150 MPa, the crack has opened 20 microns, and we see here a fully developed secondary loop. On a crack with $c=230$ mils, we measured the loop ratio at 10 values of bending stress ranging from 0 to 250 MPa (Fig. 7). The loop ratio remains at zero until we reach a stress of 30 MPa. It then jumps

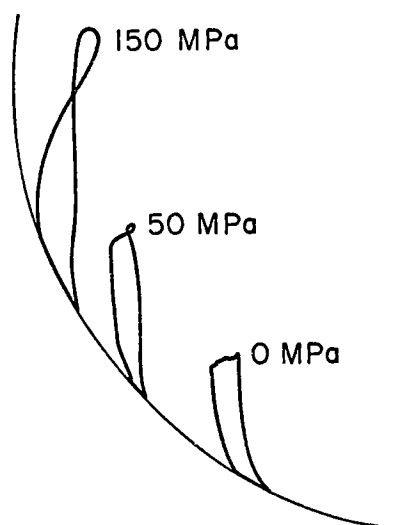


Fig. 6 FMR crack signature at several values of bending stress.

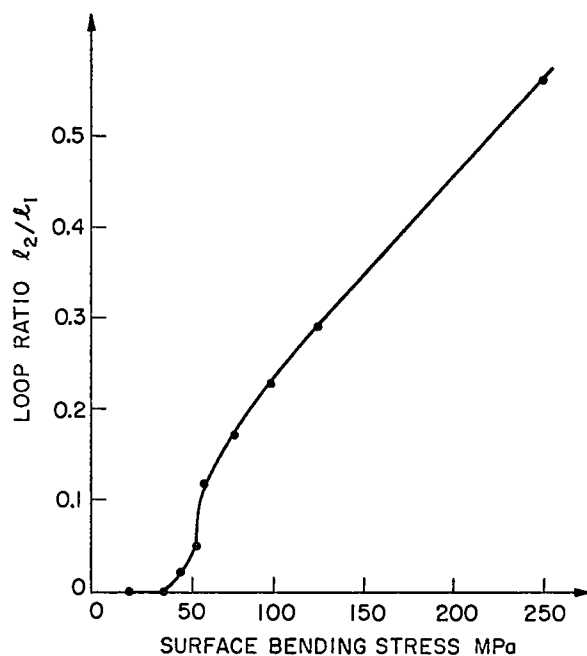


Fig. 7 Loop ratio vs. surface bending stress.

sharply, and above a stress of approximately 75 MPa, the loop ratio increases linearly with increasing bending stress. We measured the crack opening displacement optically at 8 different values of bending stress with an optical microscope, in order to compare the loop ratio with the actual crack opening. See Fig. 8. At 25 MPa, the crack had no visible opening. At 50 MPa we detected approximately 1 micron of opening, and above 50 MPa the crack opening increased linearly with increasing stress. This linear relationship is what we would expect from linear elastic fracture mechanics theory. The delay in linear behavior is caused by

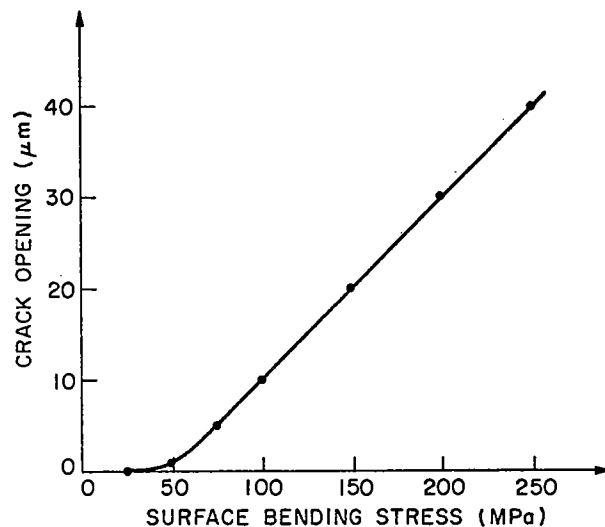


Fig. 8 Optically measured crack opening vs. surface bending stress.

the crack closure phenomenon. Briefly stated, crack closure is caused by compressive residual stresses left in the wake of the plastic zone of the advancing fatigue crack. These residual stresses leave the adjacent crack faces pressed tightly together. The elastic deformation of the crack faces due to externally applied loads must overcome the residual stress displacements before the crack will open completely. Further insight in the crack opening behavior may be obtained by comparing the loop ratio to the optically measured crack opening, as shown in Fig. 9.

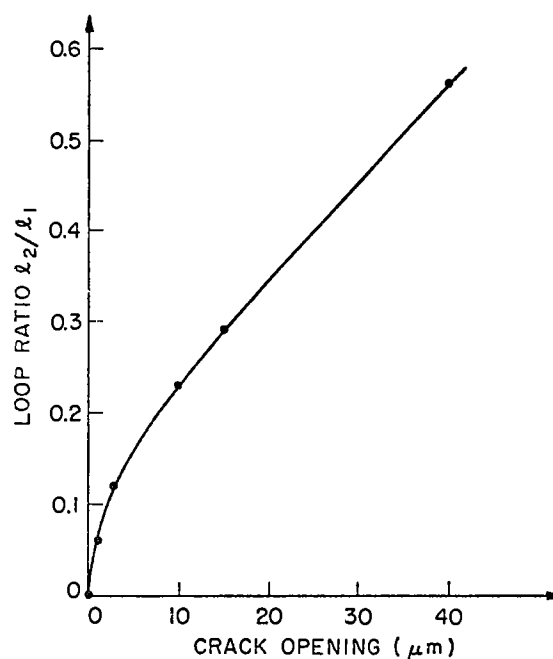


Fig. 9 Loop ratio vs. crack opening.

Here we see that the loop ratio varies in a nonlinear manner with increasing crack opening up to an opening of approximately 10 microns. After the crack opens this amount, the loop ratio varies linearly with increasing crack opening. We believe that the nonlinear behavior of the loop ratio during the initial stages of the crack opening is caused by the crack closure phenomenon. More specifically as increasing bending stress is applied the distribution of residual stress on the adjacent crack faces causes the crack to "peel open," starting at the surface. During this nonlinear opening event, the effective crack length of the fatigue crack changes with changing stress. Here the effective length is defined as the distance below the surface to where the adjacent crack surfaces just begin to touch.

ESTIMATION OF CRACK DEPTH FROM CRACK OPENING

Kobayashi³ has calculated the normalized crack opening displacement at the origin, $\Delta u_z(0,0)$, of semi-elliptical shaped surface cracks in a finite depth plate under pure bending. In Fig. 10 we show how this result may be replotted to show how the normalized crack opening $\Delta u_z(0,0)/\sigma \cdot G$, may be plotted as a function of crack depth at constant crack width. Here G is the shear modulus, and $\Delta u_z(0,0)$, σ and c have been defined previously. An estimation of the depth of an arbitrary elliptical crack may be made then by optically measuring the crack half width, applying a known bending stress, and measuring the COD at the crack center. For the sample upon which COD vs. stress measurements were taken for this work, we estimated the crack depth at $a = 192$ mils.

that the true crack depth was $a = 200$ mils. This results in an error of only 4%.

CONCLUSIONS

The electromagnetic NDE technique utilizing microwave frequency eddy currents has been shown to be effective in the detection of a closed surface crack opening displacement of a surface fatigue crack in a body subjected to three point bending. For the probe geometry described in this work, changes in the probe's complex impedance were correlated to the presence of crack opening displacement during translation of the FMR probe over an opened fatigue crack. Additionally, the Smith chart response of the interaction between the probe and a fatigue crack is found to be rich in geometric information, allowing quantization of the probe signal.

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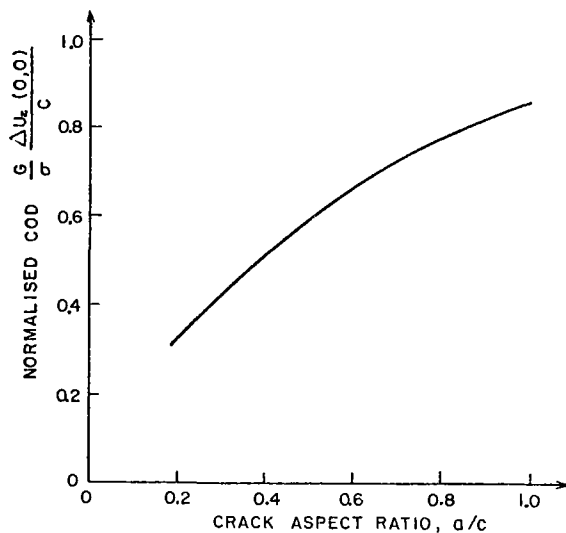


Fig. 10 Normalized crack opening vs. crack aspect ratio at constant value of crack half-width. $c = 230$ mils, with specimen thickness = 500 mils.

After COD vs. stress measurements were completed on the sample in question, the specimen was cut in half, and polished and etched to reveal

SUMMARY DISCUSSION

Jim Martin, Chairman (Rockwell Science Center): Are there any questions?

James Goff (Naval Surface Weapons Center): I suppose this was all done on clean surfaces.

Michael Resch (Stanford University): They were metallurgically prepared.

James Goff: What if some sort of dirt has gotten in the cracks, like some sort of insulating penetrant.

Michael Resch: That won't hurt us, because there is already aluminum oxide film in the open crack that is there. So if there was some dirt in there, I don't think it would effect us at all.

Frederick Vaccaro (The Timken Company): Regarding this question about an oxide in the crack or dirt in the crack: How does the crack opening displacement, then, result in the variation? Are you actually having current transfer through the crack?

Michael Resch: No, it is passing around the crack. What I tried to show is that the change in impedance is really a function of the open volume underneath the probe. There was a term that had the permeability times the crack depth times the opening over two. That is really permeability times the area of the open crack. But it is measured per unit length; for a three-D crack.

Dick Barry (Lockheed Missiles and Space): I hate to keep riding the same horse, but how did you measure the crack depth?

Michael Resch: We cut it in half, polished it, and etched it after we were finished with all of our runs.

Dick Barry: One of the reasons I bring this up is I have done this. The bottom of cracks are not always nice and uniform, and unless you go through a number of different steps in your polishing you may not find the maximum. This may be a region of error you may want to look into. It may be the average you're measuring rather than the absolute maximum depth.

Michael Resch: That's a good point.

Boro Djordjevic (Martin Marietta Laboratories): You listed 25 microns as your lift-off. How critical is it and how producible is it?

Michael Resch: We have performed experiments of comparison showing how the crack signature changes as a function of lift off. And it turns out by normalizing the loop ratio, the L_2 over L_1 , we can keep it near 25 microns. During the test, we can sometimes have variations of 10 to 15 microns difference in height. We found that that changes the loop ratio at a given crack opening depth by less than 20 percent. So to the first order, the loop ratio is relatively insensitive to errors in lift off.

Ross Waglein (Hughes Aircraft Company): Eddy current skin depth is a function of the frequency. If the crack were in fact closed, how close to the surface could it be for you to still show a detectable loop?

Michael Resch: The skin depth at a gigahertz is several microns. We do see a tightly closed crack at that size. The limit is not intuitively obvious to me. However, in general, if the crack is greater than the skin depth, I would predict we would see something.

Ross Waglein: As a function of skin depth?

Michael Resch: Yes.

Jim Martin, Chairman: If there are no more questions, we will proceed.